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The Effect of Concentrated Light Intensity on Temperature Coefficient of the InGaP/InGaAs/Ge Triple-Junction Solar Cell

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Abstract: Research on automatic tracking solar concentrator photovoltaic systems has gained increasing attention in developing the solar PV technology. A paraboloidal concentrator with secondary optic is developed for a three-junction GaInP/GalnAs/Ge solar cell. The concentration ratio of this system is 200 and the photovoltaic cell is cooled by the heat pipe. A detailed analysis on the temperature coefficient influence factors of triple-junction solar cell under different high concentrations (75X, 100X, 125X, 150X, 175X and 200X) has been conducted based on the dish-style concentration photovoltaic system. The results show that under high concentrated light intensity, the temperature coefficient of V_{oc} of triple-junction solar cell is increasing as the concentration ratio increases, from -10.84 mV/°C @ 75X growth to -4.73 mV/°C @ 200X. At low concentration, the temperature coefficient of V_{oc} increases rapidly, and then increases slowly as the concentration ratio increases. The temperature dependence of η increased from -0.346%/°C @ 75X growth to -0.103%/°C @ 200X and the temperature dependence of P_{mm} and FF increased from -0.125 W/°C, -0.35%/°C @ 75X growth to -0.048W/°C, -0.076%/°C @ 200X respectively. It indicated that the temperature coefficient of three-junction GaInP/GalnAs/Ge solar cell is better than that of crystalline silicon cell array under concentrating light intensity.

Keywords: Concentration, solar, temperature coefficient, triple-junction solar cell.

1. INTRODUCTION

Nowadays, photovoltaic power generation has attracted attention all over the world. Researches have been focusing on some difficult problems such as the cost, reliability and longevity of solar cell, system mode and optimization methods. The price of solar cell is the main cost of the photovoltaic power generation, which is the main obstacle for the large-scale application of photovoltaic power generation [1-7]. Therefore, the key point of the researches on photovoltaic power generation is to reduce the cost and improve the power generation efficiency.

Multi-junction solar cell has a phenomenon of recession under working condition because of the rising cell temperature due to the high solar radiation intensity. The working temperature of solar cell is decided by the ambient temperature, the characteristics of cooling system, solar radiation intensity and some other reasons such as wind speed. Temperature coefficient is an important parameter for the performance of multi-junction solar cell. The open-circuit voltage decreases with the rise of the cell working temperature. Though the short-circuit current slightly increases with the rise of the cell working temperature, the open-circuit voltage decreases obviously, in turn decreasing the output power and efficiency of the photovoltaic cell. Thus, for the solar cell, especially the GaInP/GalnAs/Ge triple-junction photovoltaic cell under high concentration, temperature coefficient has a significant impact on its performance [8].

Quite a few studies have been conducted in the last decade investigating the effect of temperature on characteristics of multi-junction cell. For example, the experimental studies on the electrical characteristics of a InGaP/lnGaAs/Ge triple-junction solar cell under the concentration ratio of 1~200X based on a Fresnel concentration system were presented in [9, 10]. The results showed that under the same cell temperature, the open-circuit voltage, cell efficiency and short-circuit current increased with the increase in concentration ratio. For a given concentration ratio, the open-circuit voltage, conversion efficiency and fill factor decreased with the increase in the cell temperature, while the short-circuit current increased. The relation between the cell temperature and cell efficiency was pointed out in [11]. The research indicated that the cell efficiency decreased when temperature increased. The efficiency was 39% at 25°C, but the efficiency was 31% at 100 °C. The research on the temperature coefficient of the open-circuit voltage based on Fresnel concentration system was presented in [12]. The cell temperature was between 30°C ～ 240°C and the concentration ratio was between 1X～14X. The results showed that the temperature coefficient of open-circuit voltage increased with increasing concentration ratio. There were different changes between different temperature ranges. The temperature coefficient of open-circuit voltage at 30°C ～100°C was smaller than the coefficient at 170°C～240°C. The temperature dependence of the I-V parameters from triple junction GaInP/InGaAs/Ge concentrator solar cells was developed by [13]. The concentration ratio was between 1X ～ 950X. The change range of open-circuit voltage temperature coefficient was different between different concentration ratios. The amplitude of open-circuit voltage

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temperature coefficient below 200X was larger than the amplitude greater than 200X. A high concentration PV system with one-axis tracking system was developed by [14]. A linear first stage concentrator consisting of a parabolic mirror trough focused on the solar radiation onto a row of dielectric-filled, non-imaging three-dimensional concentrator, which acted as the second stage. The geometric concentration ratio was 300X. Both GaAs cell and $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}$ as tandem cell were tested, which showed that the measured efficiency was 14.8% and 20.5% respectively. The cell temperature was 61°C, which was 39°C above the ambient temperature. A modeling of module temperature of a concentrator PV system was proposed in [15]. The experiment was based on a 300X (geometric concentration ratio) CPV which used InGaP/lnGaAs/Ge triple-junction solar cell. The maximum efficiency of this system reached 22.0%, and maximum daily average efficiency was 17.6%. The performance of C1MJ and C2MJ InGaP/lnGaAs/Ge triple-junction solar cell was investigated in [16], which under the concentration ratio was 1~1000X and the cell temperature was 0°C～120°C. The results showed that both the fill factor and cell efficiency increased first and then decreased with the rise of the concentration ratio, and they all decreased with the increase in the cell temperature. Under the same cell temperature, the fill factor reached peak value when the concentration was about 200X, while the cell efficiency reached its peak value at the concentration of about 500X. The output characteristics and output power influence factors of crystalline silicon cell array and GaAs cell array under concentration were analyzed based on trough concentrating cogeneration system [17]. Results show that the output performance of GaAs cell array was better than that of crystalline silicon cell array under concentrating light intensity. The temperature coefficient of GaAs was better than silicon cell's. When the temperature elevated by 1K, the power of GaAs cell array decreased by 0.75%, the power of polycrystalline silicon cell array decreased by 1.04% and the power of monocrystalline silicon cell array decreased by 3.19%.

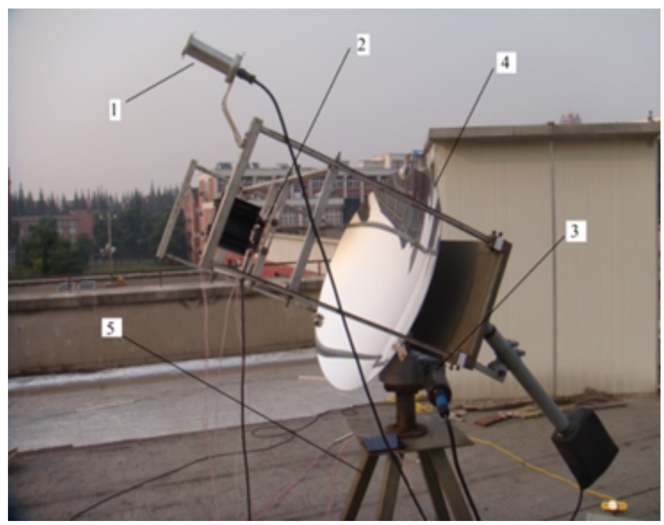
At present, research is being conducted on the InGaP/lnGaAs/Ge triple-junction solar cell chiefly in electrical characteristics such as V_{oc}, I_{sc}, FF, P and η, but the study on the temperature coefficient of an InGaP/lnGaAs/Ge triple-junction solar cell is deficient. To address such issues, this work investigates the thermal-electrical characteristics of a triple-junction InGaP/InGaAs/Ge solar cell under high concentration system. The solar cell is cooled by a heat pipe and a homogenizer is introduced to keep the light uniform. The performance of the solar cell and the concentration system is examined under realistic outdoor conditions using a sun tracking system.

2. EXPERIMENTAL SYSTEM AND MEASURING EQUIPMENT

2.1. Experimental System

The experimental system included a high concentration system, a sun tracking system, a multi-junction solar cell, and a heat-pipe based cooling system, as shown in Fig. (**1**). The experiments were conducted on a 0.5×0.5 cm^2 triple-junction InGaP/InGaAs/Ge solar cell which was manufactured by Shenzhen Yin Xuan Sheng Technology Co., Ltd, as shown in Fig. (**2**). The advantages of this solar cell include better light absorption coefficient, smaller temperature coefficient and higher efficiency and so on.

In general， the incident angle range that the system could receive sunlight would decrease with the increase of concentration ratio. It should use tracking system in order to ensure concentration performance, if a concentration ratio is exceeding 10. Thus, a high precision tracking system is critical to the high concentration photovoltaic system [18]. The concentrating photovoltaic system in this work had a double-axis solar tacking system, which controlled the azimuth angle and the elevation angle with an accuracy of ±0.5°. To maintain a better cooling effect of the multi-junction solar cell, a heat pipe heat exchanger system was employed to dissipate the heat generated especially under high concentrating ratio. The heat pipe heat exchanger used in this paper was made of copper. Evaporation part of heat pipe exchanger was soldered onto the back of the solar cell through a high conductive thermal grease, which reduced thermal contact resistance in between. The heat pipes isothermally supplied heat to a series of cooper fins located at condensing section of the heat pipe. Then the heat was transferred from the fins to the air by natural convection. As the operating temperature range was 0°C～100°C, the working fluid was water, and the charging ratio was 30%.



1-solar monitor; 2-solar cell module; 3-transmission mechanism; 4- concentrator; 5- Support

Fig. (1). Dish-style concentrating photovoltaic system.

2.2. Measuring Equipment

Field tests of the CPV were carried out on the roof of a building inside the University of Shanghai for Science and Technology (Shanghai, China). Fig. (**2**) shows the arrangement of the measurement system. The module temperatures were measured by thermocouples (T type, ±0.1°C) and recorded by an Agilent 34970A data acquisition system. Direct solar radiation was measured by a pyrheliometer (TBS-2-2, manufactured by Jinzhou Yangguang meteorological science and technology Co., Ltd) fixed to the module every 30 seconds, as well as the weather data such as wind speed and direction, atmospheric temperature, humidity and global solar radiation. The PV module output and voltage at maximum power point were measured by an I-V tracer (IT8500, manufactured by ITECH Electronic Co., Ltd) every 60 seconds (Fig. **3**).

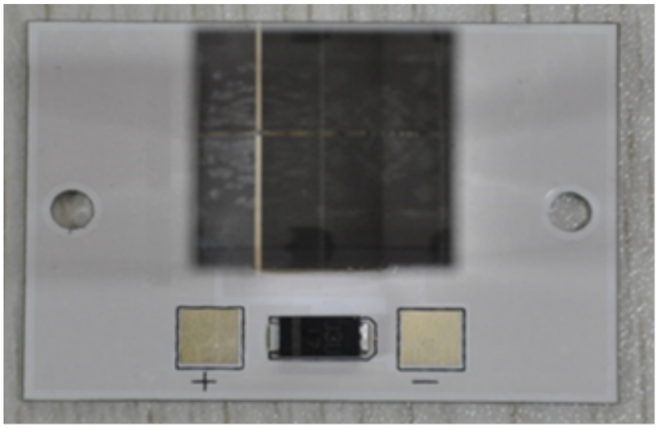


Fig. (2). Three junction GaInP/GalnAs/Ge solar cell.

3. THE CONCENTRATION SYSTEM

The InGaP/InGaAs/Ge triple-junction solar cell can operate above 1000 suns, because of its excellent performance under high temperature. The concentration ratio used in the experiment was from 75X to 200X. A two-stage concentration system was used in the experiment, where the solar radiation was firstly received by the first-stage concentrator, which concentrated further by reflection into the second stage concentrator (homogenizer). The shape and structure of the second stage concentrator used in the experiment are shown in Fig. (**4**).

Assuming that the short circuit current is proportional to the incident radiation flux, the concentration ratio of the dish-style concentrating photovoltaic system is expressed as:

$$FF = \frac{V_{mm} \times I_{mm}}{V_{oc} \times I_{scx}} \quad (1)$$

Thus, the cell efficiency, ηc, is defined as the maximum output power divided by the incident power on the cell:

$$FF = \frac{V_{mm} \times I_{mm}}{V_{oc} \times I_{scx}} \quad (2)$$

Fill factor can be defined as:

$$FF = \frac{V_{mm} \times I_{mm}}{V_{oc} \times I_{scx}} \quad (3)$$

The peak power is:

4. RESULTS AND DISCUSSION

4.1. The Temperature Coefficient of Open-Circuit Voltage

The temperature coefficient of V_{oc} of the GaInP/GalnAs/Ge triple-junction photovoltaic cell changing with the concentrating ratio is shown in Fig. (**5**). With the increase in concentrating ratio, temperature coefficient gradually increases from -10.84 mV/°C under 75X to -4.73 mV/°C under 200X. The rising cell temperature leads to narrow band gap. Recombination rate of the depletion layer gets bigger and output voltage decreases. The growth under low concentration is bigger than that under high concentration. It is mainly because with the rise in the concentration, photo flux density is bigger, which leads to the increase in minority carrier concentration and short-circuit current density. Compared with the forward current

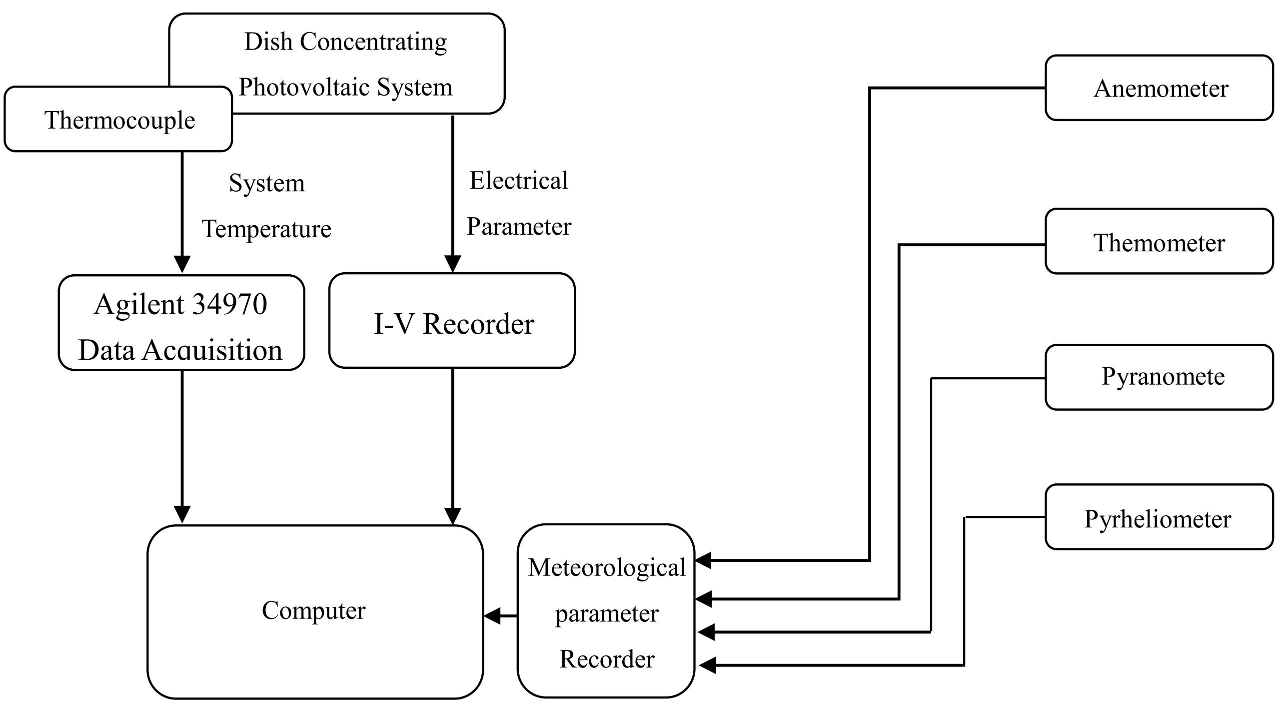


Fig. (3). Dish concentrating photovoltaic system performance test platform.

density, dark saturation current density has smaller impact on V_{oc}, which gradually decreases the temperature coefficient of V_{oc}. It can be concluded that with the rising of concentrating ratio, the effect of the concentrating ratio on temperature coefficient of V_{oc} gradually decreases.

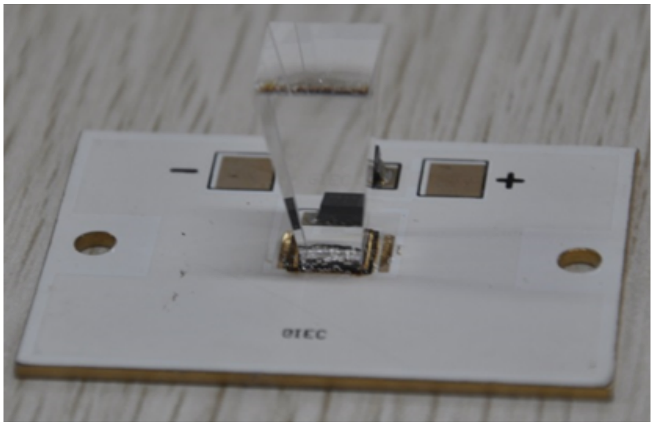


Fig. (4). The three junction GaInP/GalnAs/Ge solar cell with homogenizer.

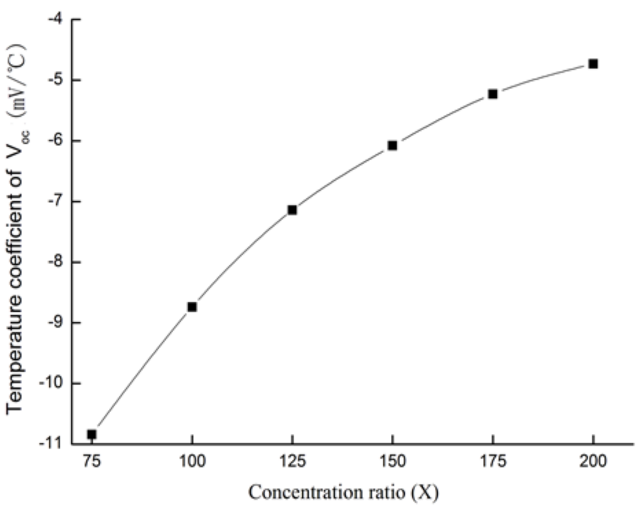


Fig. (5). The temperature coefficient of V_{oc} as a function of concentration ratio.

4.2. The Temperature Coefficient of Short-Circuit Current

The temperature coefficient of I_{scx} of the GaInP/GalnAs/Ge triple-junction photovoltaic cell changing with the concentrating ratio is shown in Fig. (**6**). With the increase in concentrating ratio, temperature coefficient gradually increases from 3.33 mA/°C under 75X to 47.6 mA/°C under 200X. The rising cell temperature leads to narrow band gap, which makes photons acquire enough power to create electron-hole pairs. The growth under low concentration is shorter than that under high concentration. It can be concluded that with the rise in concentration ratio, the effect of the concentration ratio on temperature coefficient of I_{scx} gradually decreases.

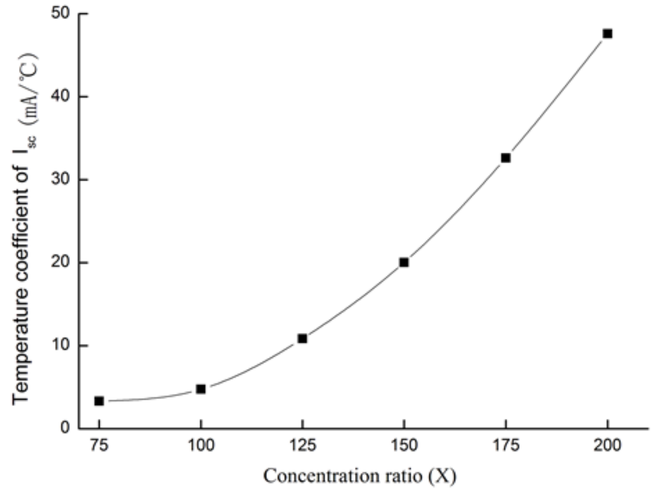


Fig. (6). The temperature coefficient of I_{sc} as a function of concentration ratio.

4.3. The Temperature Coefficient of Peak Power

The temperature coefficient of P_{mm} of the GaInP/GalnAs/Ge triple-junction photovoltaic cell changing with the concentrating ratio is shown in Fig. (**7**). This is mainly because with the rise in the concentrating ratio, cell temperature increases and semiconductor intrinsic carrier concentration falls sharply, which lowers the contact potential difference of the balance P-N junction. Dare current of the P-N junction increases and the V_{oc} decreases, decreasing the peak power with the rise of temperature. The experimental results show that different from the temperature coefficient of V_{oc} and I_{sc}, the temperature coefficient of P_{mm} presents a nearly linear increase with the increase in the concentration ratio when the concentration ratio is below 150X. When the concentration ratio is over 150X, the temperature coefficient of P_{mm} shows a gradually decreasing trend with the increase in the concentration ratio.

4.4. The Temperature Coefficient of Fill Factor

The temperature coefficient of *FF* of the GaInP/GalnAs/Ge triple-junction photovoltaic cell changing with the concentrating ratio is shown in Fig. (**8**). With the increase in concentrating ratio, temperature coefficient gradually increases from -0.35%/°C under 75X to -0.076%/°C under 200X. The experimental results show that the temperature coefficient of *FF*, like that of peak power, presents a nearly linear increase with the increase in the concentration ratio when the concentration ratio is below 150X. When the concentration ratio is over 150X, the temperature coefficient of *FF* shows a gradually decreasing trend with the increase in the concentration ratio.

4.5. The Temperature Coefficient of Cell Efficiency

The temperature coefficient of η_c of the GaInP/GalnAs/Ge triple-junction photovoltaic cell changing

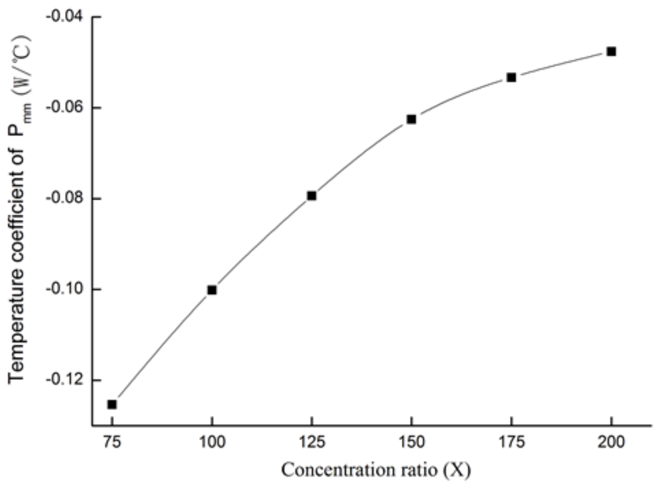


Fig. (7). The temperature coefficient of P_{mm} as a function of concentration ratio.

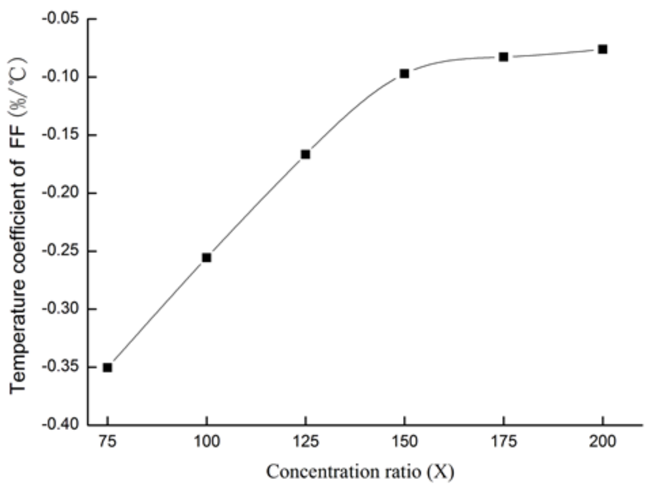


Fig. (8). The temperature coefficient of *FF* as a function of concentration ratio.

with the concentrating ratio is shown in Fig. (**9**). With the increase in concentrating ratio, temperature coefficient gradually increases from -0.3457(%/°C) under 75X to -0.103(%/°C) under 200X. It is mainly because with the increase in concentrating ratio, V_{oc} should increase with the logarithm of light intensity and the significant change of V_{oc} causing a decrease in ηc with the rise of temperature. The experimental results show that the temperature coefficient of η_c presents a nearly linear increase with the increase in the concentration ratio. When the concentration ratio is over 150X, the temperature coefficient of η_c shows a gradual decreasing trend with the increase in the concentration ratio. The growth under low concentration is bigger than that under high concentration. It is obvious that concentrating ratio has an important effect on the temperature coefficient of η_c.

CONCLUSION

The temperature coefficient of V_{oc} and η_c increases with the rise of concentrating ratio, but the increased rate gradually reduces. While the temperature coefficient of I_{scx} also increases with the rise of concentrating ratio, but the increased rate gradually rises. The temperature coefficients of P_{mm} and *FF* present a nearly linear increase with the increase in the concentration ratio when the concentration ratio is below 150X. When the concentration ratio is over 150X, the temperature coefficients of P_{mm} and *FF* show a gradually decreasing trend with the increase in the concentration ratio.

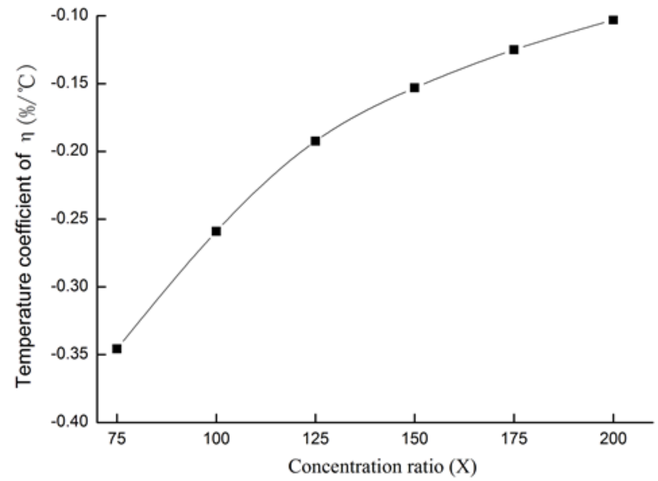


Fig. (9). The temperature coefficient of η_c as a function of concentration ratio.

Concentrating ratio and cell temperature are the main factors of output power and conversion efficiency under high concentrating photovoltaic system. Therefore, by improving the concentrating ratio of the reflective concentrator and developing efficient and reliable radiator, the temperature may influence the electrical characteristics of photovoltaic cell, thus improving the performance of the whole concentrating photovoltaic system.

NOMENCLATURE

η_c	cell efficiency	%
E_d	direct solar radiation	$W{\cdot}m^{-2}$
A_c	cell area	m^2
V_{mm}	maximum power point voltage	V
I_{scx}	short-circuit current under concentrated light	A
FF	fill factor	%
η_r	optical efficiency of concentrator	%
C	concentration ratio	
V_{oc}	open circuit voltage	V
I_{mm}	maximum power point current	A
I_{sc}	short-circuit current under 1 sun illumination	A
P_{mm}	load current	W

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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